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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

This Issue

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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Petroleum Laboratory Investigations

BECAUSE of the complexities of modern machines, materials, processes and associated operations, industrial problems associated with petroleum products now adopt many disguises or concealments and are becoming increasingly difficult to detect. The unaided physical senses of even a highly trained investigator are no longer adequate. He must increasingly depend on the specialists and scientific equipment of extensive petroleum laboratories to find and evaluate minute clues, to trace their most probable causes and to recommend correctives.

The petroleum laboratory's investigation must frequently employ task forces composed of engineers of all types, organic and inorganic chemists, metallurgists, bacteriologists, physicists, toxicologists, physicians, agronomists, photographers, dermatologists and other specialized technical personnel. These in turn must be equipped not only with such intricate and costly scientific equipment as is commercially available, but also with special equipments designed and built by the laboratory's own scientists and therefore found nowhere else.

This article will present brief reports of several investigations which will illustrate: the wide variety of problems that one major petroleum laboratory has encountered; the scientific approach, extensive equipment and technical ingenuity that are frequently required to obtain accurate diagnoses; and the mutual profit afforded by intensive cooperation between the customer-user and the petroleum company.

An Aviation Valve Problem

An airlines company complained of wide-spread sticking of exhaust valves in a particular make and model of twin-engined aircraft and attributed it to the aviation engine oil in use. Valve stems, tulips and guides were coated with excessive deposits, causing interference fits and sticking. In his investigation, the oil engineer also found that valve rocker box gaskets were deteriorating quickly and that spark plug electrodes were fouling with a white glassy material. He then discovered that all such failures throughout the air fleet were confined to the starboard (right-side) engines, while the port engines which used the same oil (although from separate tanks) were untroubled.

Chemical analyses of the valve deposits showed them to be composed of a complex lead-bromine-phosphorus compound, phosphorus being a foreign element not present in either the gasoline or the *new* engine oil. However, the analyses of several different samples of *used* crankcase oil all showed high phosphorous content. This was further traced to contaminating leakage through the seals of the cabin supercharger drive which was driven solely by the starboard engine and lubricated with a phosphorus-base hydraulic fluid. The complaint was solved and the crankcase oil absolved by installing a pipe to

Figure 1 — Micro hardness tester.

drain away any supercharger drive leakage, thereby preventing contamination of the starboard engine and its lubricating oil.

A Bus Bearing Problem

A large motor bus operator suddenly began to experience severe corrosion of copper-lead engine bearings. Though of very high quality and protectivity, the motor oil was at once accused. Preliminary chemical analyses seemed at first to confirm the indictment since used oil from engine crankcases would definitely attack both lead and copper. But further analysis determined the presence of *free* elemental sulfur, never a legitimate constituent of an engine oil. Only after a detailed step-by-step investigation by a field engineer was the sulfur trailed to its source — a recent change to a new and cheaper type of oil filter cartridge in which the spool parts were stuck together with elemental sulfur! That purchasing agent certainly saved no money for the operator!

An Hardness Problem

The hardness of a chemically-pure solid compound is one of its several important physical characteristics and can therefore be used in helping to identify it. However, it is not generally realized that most common engineering materials are mixtures or combinations of several pure compounds, consequently the hardness of the bulk material will vary widely depending upon where the hardness measurement was obtained and what pure compounds in the close vicinity of the measurement were actually responsible for the result. Thus the ordinary hardness measurement is merely a "bulk", "average" or "general" determination over a relatively large area: it is neither confined nor selective nor precise enough to measure the hardness of tiny material components such as individual crystals and inclusions.

Fortunately for the laboratory technologists and the customers they serve, the very special hardness measuring device illustrated in Figure 1 has become available in recent years. Its basic features include (1) a finely-finished diamond-shaped indenter or test point, (2) a means for applying any of a wide range of accurately measured loads so as to force the indenter into the unknown material, (3) a specimen holder with micrometer adjustments to accurately locate the desired point of indentation and (4) an optical system with high magnification used initially to select the point of indentation and subsequently to measure the length of the diamond-

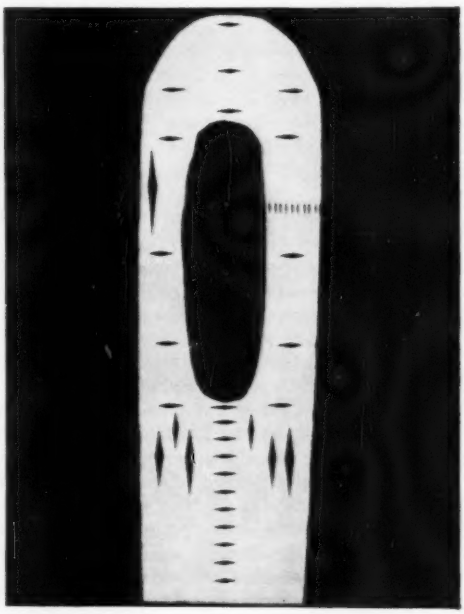

Figure 2 — Micro hardnesses on needle eye.

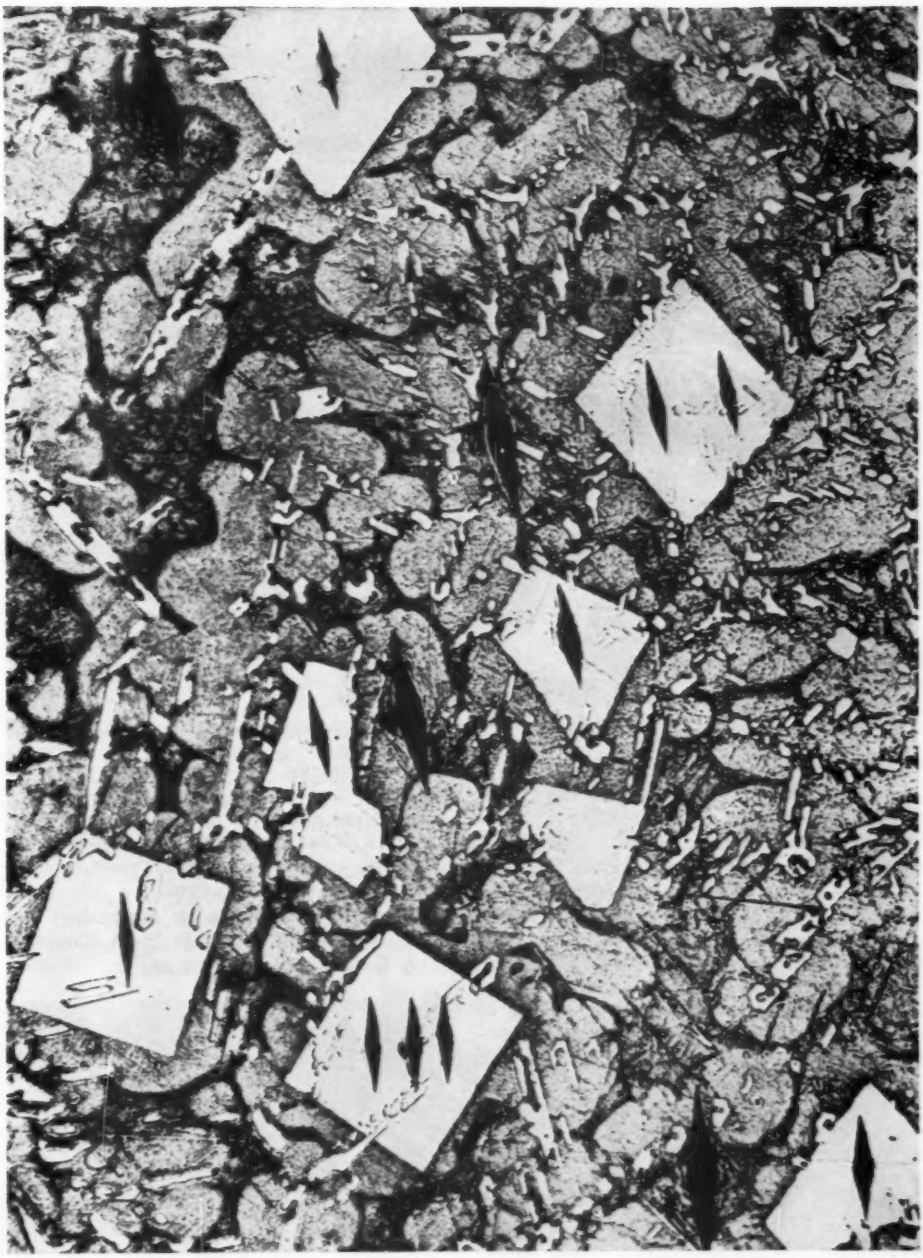

Figure 3 — Photomicrograph of tin base babbitt.

shaped indentation. For a given load, the length of the resultant indentation is a measure of the materials' hardness and can be readily converted to such other more common hardness measurement scales as the Brinell and Rockwell. For convenience in handling, the specimen to be examined is frequently molded into the top surface of a bakelite block.

Figure 2, the greatly enlarged photograph of the

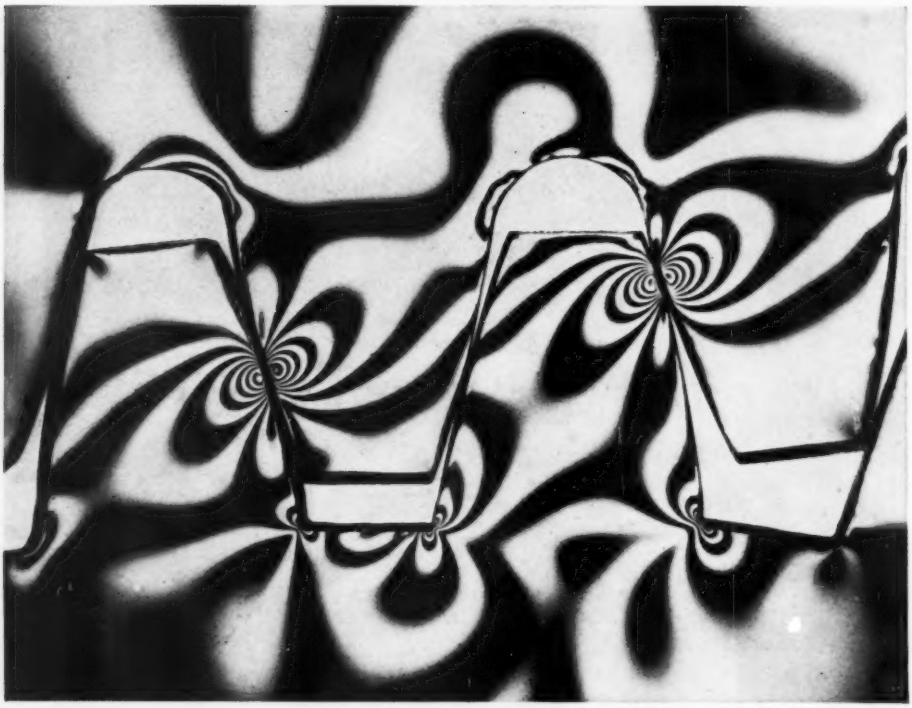

Figure 4 — Photoelastic effect (transmission of polarized light through loaded plastic gearing).

eye in a small steel sewing needle, presents a spectacular example of the applicability of this special apparatus. The large diamond-shaped indentations were made with a heavy load on the indenter; small indentations were caused by light loads. The uniform length of the medium-sized horizontal diamonds indicates that the needle was quite uniformly hardened throughout the examination area. Note particularly that the high precision of the instrument permitted no less than ten separate hardness measurements to be taken across the narrow sidebar of the needle's eye.

Figure 3, a photomicrograph at 250 diameters of a tin base babbitt bearing alloy, gives another example of the selectivity of this hardness tester. Such an alloy is normally composed of about 91% tin with 4½% each of antimony and copper. The large square white objects are actually tiny and normally-invisible cubical crystals of a definite tin-antimony alloy, surrounded by the grey-colored matrix composed essentially of tin. The several diamond-shaped impressions illustrate the ability of this hardness tester to preselect and measure individual tin-antimony crystals, in fact three such measurements were easily made on a single crystal. Since one indenter load was used throughout this sample, the lengths of the various diamonds directly indicate differences in hardness, the tin-antimony crystals being relatively hard in comparison with the soft tin matrix. Some plain bearing experts theorize that the hard crystals in such an alloy carry most of the load while the softer matrix merely holds and allows them to conform to the journal.

For additional examples of applications of this equipment see the "Aircraft Drive Pinion" and "Spur Gear Wear" Problems on Pages 38 and 41.

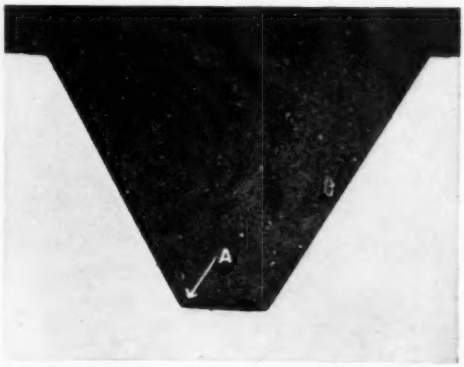

Figure 5 — Photomicrograph (50X) of aviation cylinder-barrel thread.

A New Car Gumming Problem

An automotive manufacturer suffered severe carburetor gumming and intake valve sticking almost before new cars rolled off the assembly line, and the gasoline was immediately blamed. Associated with the deposits, however, the petroleum laboratory chemists found zinc chloride, not only a common ingredient of soldering fluxes but also a powerful catalyst in forming gasoline gum. The gum trouble stopped when the gasoline tank manufacturer did a more thorough job of washing flux residues from his tanks.

A Gear Tooth Design Problem

As subsequently illustrated on this page in the "Cylinder Barrel Problem" and the "Worm Gear Problem", seemingly insignificant details in design or manufacture of a machine element can have tremendous effects on its useful life. Furthermore, design detail quickly becomes hypercritical when load or speed or temperature is increased.

Figure 4 is presented to illustrate the effect of a detail in the design of a certain gear, as demonstrated by the photo elasticity method. The two gears shown were accurately machined from a transparent plastic, mounted on correctly spaced axes in a loading frame with one gear fixed and the desired torque applied to the other. When polarized light is projected through such a plastic while under stress, the existence and distribution of the internal stress in the gears is indicated by changes in the optical properties of the plastic such that it produces a series of rainbow-colored fringes and bands of significant width and shape. Though the black and white image of Figure 4 is neither as colorful nor as spectacular as the image in the polariscope, it is actually more useful for analytical purposes as the fringes are more sharply defined and can be counted more easily. A monochromatic illuminant such as the green line of the mercury arc produces very sharp, crisp stress fringes well suited for stress analysis. Furthermore, it seems that the narrower the band, the higher the stress gradient; contrariwise a broad band or patch locates a more uniform stress distribution and oftentimes a less dangerous stress situation.

The reader's attention is now invited to the point of contact between the two gear teeth on his left where the existence of high load is indicated by the close spacing between a series of multiple concentric bands. Of interest but of secondary importance is the fact that the two teeth on the reader's right are sharing part of the total load.

Also notice that the innermost fringe is essentially circular in shape which means that the maximum stress intensity is located in the worst possible place as far as endurance life is concerned – near the already overworked tooth surface. In fact the peak stress can be seen to exist a very short distance beneath the contact point (and not at the surface) which accounts for the shallow depth to which fatigue metal spalls out on an overworked pinion.

Now observe that the junctions between the tooth surfaces and body of the lower gear are sharp right angles and that stress fringes have concentrated dangerously at these points. An actual gear made to the same design would be prone to tooth breakage. At the opposite extreme, the teeth of the upper gear are filleted or radiused at their roots, which effectively modified the stress pattern into wide harmless patches of low intensity. In summary, these two plastic gears nicely illustrate the major importance of a seemingly minor change in design or construction.

A Cylinder Barrel Problem

An airlines operator reported that cracks were being found in cylinder barrels on aircraft engines of a particular make and model that had previously given excellent service.

The petroleum engineer investigated and determined that all cracks started on the exhaust side of the cylinder-head threads, then progressed circumferentially around the barrel for several inches or until the cylinder head was blown off entirely.

As illustrated in Figure 5, a photomicrograph of the sensitive barrel section was obtained which showed that the sub-contractor who manufactured the barrels had omitted the specified 0.005-inch radius at point A in the root of the thread. The resultant concentration of stress at the higher operating temperatures near the exhaust valve was responsible for the accelerated fatigue cracking. The "Gear Tooth Design Problem" on this page illustrates a similar effect at ordinary temperature.

A Worm Gear Problem

A truck operator complained that because of incorrect lubrication, excessive wear had occurred on the bronze worm gear shown in Figure 6. To an expert eye this "wear" seems to be the spalling or

Figure 6 – Damaged bronze worm gear teeth.

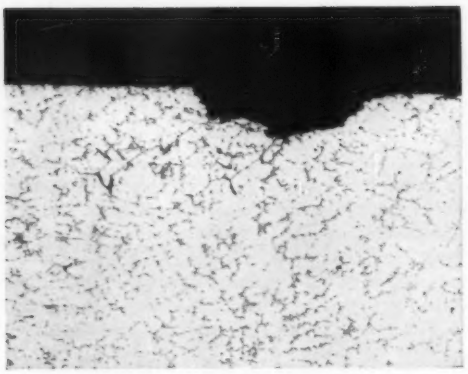

Figure 7 — Photomicrograph (50X) of tooth cross-section.

flaking which is typical of a fatigue or material failure. Furthermore the fact that all the spalled areas are on the same end of the teeth suggests a concentration of load caused by misalignment between the worm and worm gear. Such misalignment could be caused either by inaccuracy during the original manufacture or by the subsequent application of excessive loads which warped the gear case and gears out of alignment.

To obtain confirmation, however, the oil engineer forwarded the worm gear to his supporting laboratory which sectioned the spalled area of a representative tooth and obtained the photomicrograph presented as Figure 7. Careful examination of this micrograph will show a series of fine and frequently inter-connected cracks leading to the left and downwards from the spall "crater". The crater itself was originally formed by sub-surface fatigue failure of the bronze and the photograph illustrates the progressive extension of this failure.

All materials lose strength as their temperature is raised and bronze does so very rapidly. Unlike all other gearing, the contact between a worm and worm gear is wholly of a sliding nature and not easily lubricated. It might therefore be argued that a lubricant with inadequate load-carrying ability could be responsible for such a failure since it would permit higher friction and higher operating temperature, which in turn reduce the strength of the material as well as its resistance to fatigue. In this instance, however, the obvious concentration of load and damage on half the tooth surface would completely absolve any lubricant.

A Monday Problem

One summer Monday morning all the girls in a midwestern factory complained of reddening and severe itching on their legs. Whether through mere reflex action in this emergency, or as a deliberate means of getting top notch technical assistance quickly and cheaply, the manufacturer summoned the oil engineer. But within four days and before he had hardly begun, the complaint vanished as mysteriously as it had appeared. The investigation of any sporadic or non-repetitive complaint is always difficult and this was particularly frustrating.

But on another Monday morning almost exactly a year later, the girls again complained of intense itching. The reopened investigation disclosed that both Monday mornings had followed company picnics on the preceding Saturdays and that the "dermatitis" was actually the result of "chiggers" or "redbugs". These microscopic but potent insects are prevalent in the grasses and bushes of the midwest and brush off to bury themselves in the skin of the unwary passerby. Intense itching occurs which subsides however without treatment in four or five days. As is so often true, this was definitely a non-petroleum case, though it could have been prevented by advance dusting with a petroleum by-product – sulphur powder.

An Instrument Bearing Problem

As illustrated in Figure 8, unbelievably small precision ball bearings are now made for instruments and control mechanisms in aeronautic and missile applications. Though the *quantity* of grease required is microscopic (they are factory-lubricated with a tiny drop through a hypodermic needle), the *quality* of the grease for a particular intended application is extremely important. Since several different greases were used in a certain bearing plant, confusion occurred and the manufacturer's problem was to be able to quickly detect and correct confusion by being able to identify the grease in random sample bearings from his production line.

The petroleum laboratory solved the manufacturer's problem by developing a simple identification method which is now used routinely as a production check. The bearing with its grease charge intact is placed in a tiny beaker covered with a paper strip impregnated with a suitable chemical reagent. When warmed for about two hours the

Figure 8 — Instrument ball bearing 0.10 inch OD.

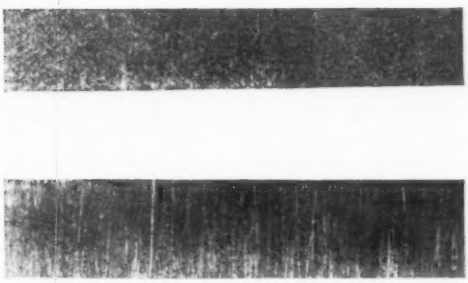

Figure 9 — Aviation piston rings (cylinder contact surfaces).

paper strip develops a distinctive color that can be matched with similar strips from known greases. This is another example of identification by comparative rather than absolute methods.

An ATF Dermatitis Problem

An automobile manufacturer reported that soon after beginning to use it, a certain brand of ATF (Automatic Transmission Fluid) caused dermatitis on employee hands and forearms, that both the union and the city health department had joined in the complaint, and that the latter was threatening to close the entire plant. The oil engineers' investigation first disclosed that another much-larger automobile manufacturer had been using vast quantities of the same fluid for more than three years without difficulty, which indicated something peculiar in the complainant's factory or usage. Further investigation showed that only a few employees were affected and that all were employed in the transmission testing department. On-the-spot observation of the test stands showed that when a pressure relief valve on each transmission automatically opened, the test operator's hands and arms were sprayed with fine but penetrating droplets of ATF. Furthermore, the plant's sanitary facilities were so distant that the operators merely wiped themselves off with a rag and washed only at home, thus both the amount and length of exposure were far greater than necessary.

As is usually true, the all-important accurate diagnosis is most difficult while the cure is simple. In this instance the problem was solved by the installation of protective shields on the test stands and the provision of adequate washing facilities near them.

An Aviation Piston Ring Problem

An airlines operator complained that piston rings, and especially the top rings, were wearing out very rapidly with consequent high oil consumption, some piston-ring land breakage, and some complete piston and engine failures. Figure 9 at 8-diameter magnification shows a side view of the chrome-plated top ring (distinguished by its etched appearance), and the plain cast iron second ring (with noticeable surface scratching). Figure 10 at 15-diameter magnification presents a cross-sectional view of the wedge-shaped chrome-plated top ring in its grossly worn groove. The chrome-plated peripheral coating on what was supposed to be the major wearing surface is plainly evident.

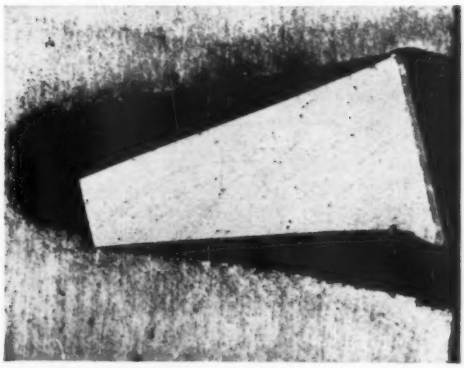

Figure 10 — Photomicrograph (15X) of cross-section of worn aviation top ring in piston ring groove.

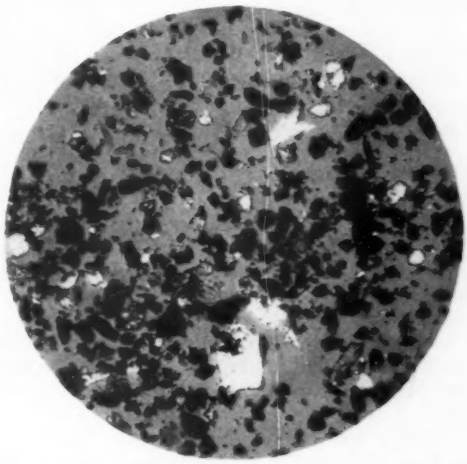

Figure 11 — Photomicrograph (100X) of extraneous abrasives (quartz, steel, silicon carbide).

By examining the airline's maintenance records, the petroleum engineer determined that practically all cases of excessive wear had originated in used cylinders that had been reconditioned by the airline. Several newly overhauled and "cleaned" cylinders still in stock were washed with solvent and each was found to contain from 34 to 104 milligrams of the foreign material magnified to 100 diameters and shown in Figure 11. X-Ray diffraction analysis of the foreign material identified it as an extremely abrasive mixture of quartz, steel particles and silicon

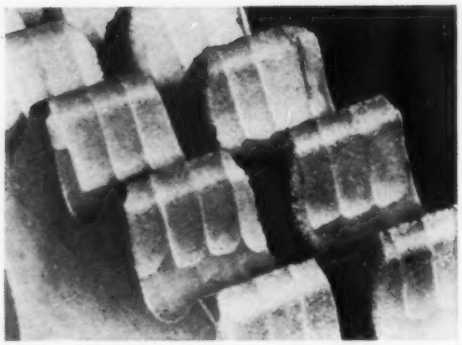

Figure 12 — Worn chain-drive sprocket.

carbide. In other words, and because of inadequate cleaning procedures during overhaul, this operator had "built in" his wear with foreign abrasives.

Since aircraft engines do not use air cleaners, similar excessive wear will occur when planes are operated off dirt runways or in dusty desert country.

A Rusty Wrist Pin Problem

A manufacturer using soluble cutting oil while grinding steel engine wrist pins suddenly experienced severe rusting of these finely-finished parts which ruined them overnight. Since a good soluble oil has considerable rust-prevention capacity, the oil in this case was blamed.

But a bacteriologist with his powerful microscope found swarms of a bacillus common to sewage in the soluble oil emulsion, and demonstrated that this bacillus had the hitherto unsuspected ability of disintegrating soluble oil emulsions and ruining their rust preventive qualities. Since purification of the water was impractical, a bactericide was used to correct this rusting problem.

A Chain Sprocket Problem

The user of a machine which employed a silent chain and sprocket drive complained that the cast iron *driven* sprocket, as illustrated in Figure 12, wore excessively and that presumably the lubricant was at fault. In this instance, the investigating lubrication engineer may have missed an opportunity to solve the complaint right on the spot by merely noting whether or not the *driving* sprocket was similarly worn. The driving sprocket receives the same lubricant and the chain subjects it to the same tooth loading: if it were also made of cast iron but was *not* worn, the lubricant would have been absolved automatically.

In the absence of this field observation, metallurgists of the supporting laboratory sectioned and polished a representative sprocket tooth, etched it, and using the research metallograph illustrated in Figures 13 and 14, obtained the metallograph or photomicrograph of the metallic structure illustrated in Figure 15. In this structure, the thread-like flakes of graphite in the right hand part of the photograph represent a long-wearing cast iron, however, the dot-like graphitic clusters in the left hand portion are characteristic of a cast iron with unsuitably low wear resistance. Obviously, no lubricant could be expected to correct such a metallurgical variance.

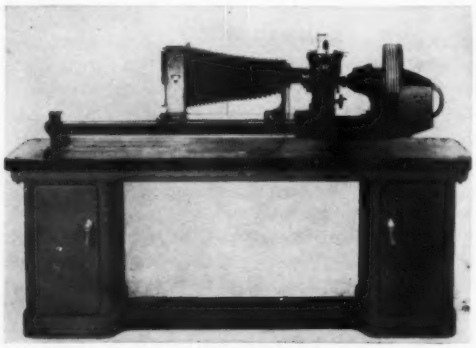

Figure 13 — Research metallograph.

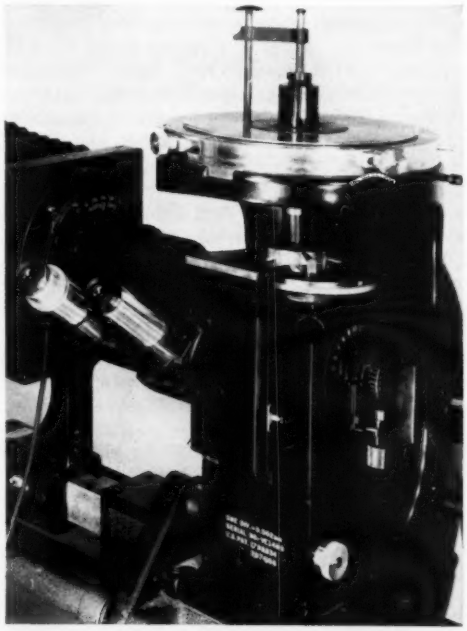

Figure 14 — Research metallograph; close-up of specimen mount.

An ATF Depreciation Problem

Within a few hours the new automatic trans-

Figure 15 — Photomicrograph of variable-structure cast iron.

missions from the production line of a well-known manufacturer began to sludge up severely and, of course, the ATF (automatic transmission fluid) was blamed. Chemical tests on the complex fluid additives seemed to confirm since they showed severe degradation both in additive quantity and quality. But continued investigation by the oil engineer discovered that a newly-installed heat exchanger in the factory's fluid-fill system was not only severely overheating the fluid, but that several leaks in the exchanger allowed high pressure super-heated steam to be injected into the fluid to complete its destruction. In brief, the fluid's "faults" were corrected by the installation and proper operation of a good heat exchanger.

A Capillary Tubing Problem

Metallic capillary tubing is widely used in household refrigerators as a simple, inexpensive and highly reliable method of expanding the refrigerant to a lower pressure and thus producing a cooling effect. One manufacturer, however, began to experience stoppage of this important tube shortly after his refrigerators were sold and placed in service. Oil for the refrigerating compressor circulates freely throughout the system and was therefore a prime suspect. Since the internal bore of such a capillary is only a few thousandths of an inch in diameter, a tiny amount of any solid contaminant in the system would eventually reach its upstream end and clog it.

Figure 16 illustrates a greatly enlarged cross-section of such a capillary with deposit beginning to form within it. Figure 17 presents a longitudinal section of another sample capillary at the point where its upstream end is brazed into an intake fitting. It will be noticed that the brazing operation has constricted the tube at this critical point and that all the deposit has formed downstream therefrom.

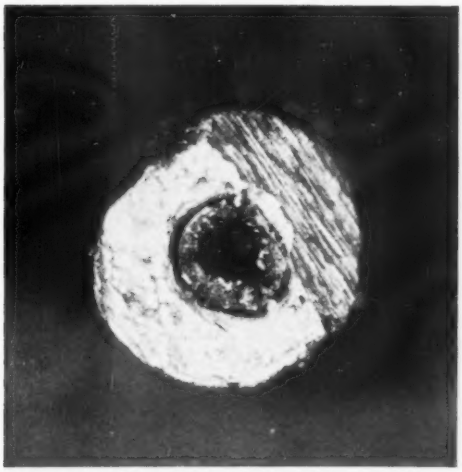

Figure 16 — Cross-section of capillary tube with internal deposit.

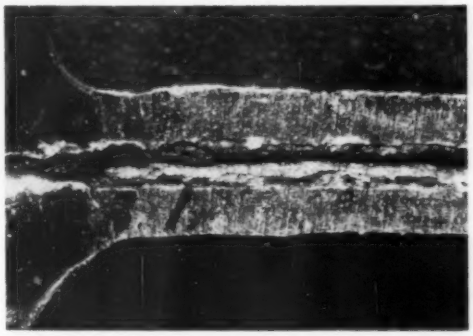

Figure 17 — Longitudinal section of capillary brazed joint and internal deposit.

With this evidence to guide him, the oil engineer recommended (1) better methods of cleaning each refrigerating system more thoroughly of manufacturing contaminants before charging the refrigerant and compressor oil and (2) a method of locating and brazing the capillary which prevented constriction. The manufacturer enthusiastically adopted these recommendations and solved his capillary tubing problem.

A Fuse Head Problem

During the manufacture of a military fuse head, a tiny hole was drilled. The girls operating the sensitive drill presses complained that their hands were being reddened with typical dermatitis and the manufacturer assumed that soluble cutting oil used in drilling was the cause. Investigation first disclosed that the girls were required to hold the fuse heads during the delicate drilling operation and were therefore in close and continual contact with the fuses. Further search developed that in the just-preceding manufacturing step the fuse heads had been washed in a special solvent, that they were still

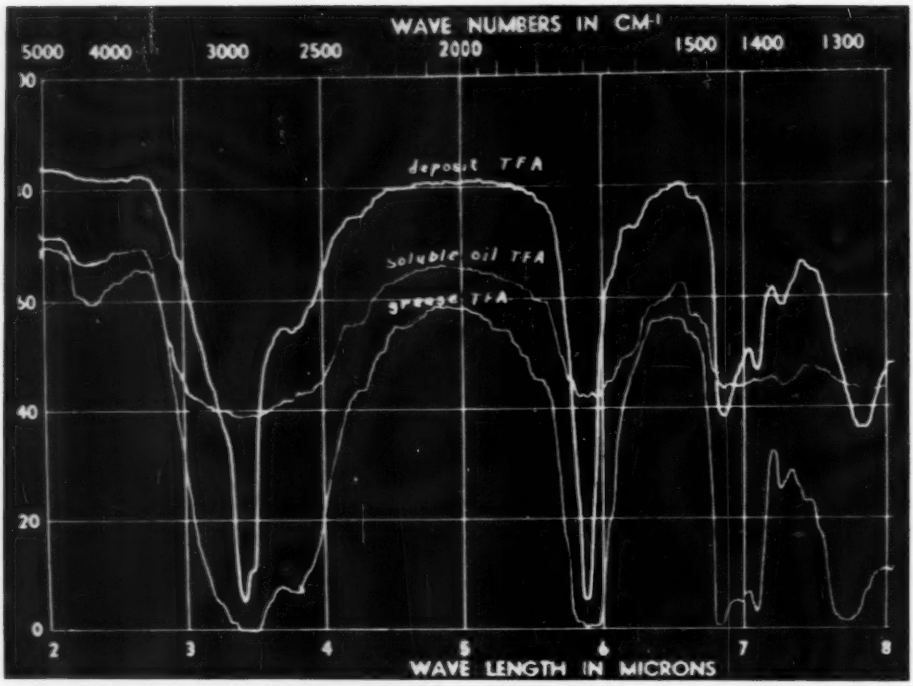

Figure 18 — Infra-red absorption spectrographs of three fatty acid samples.

wet when delivered to the girls and finally, that the solvent itself was causing the dermatitis. Change to another and more volatile solvent solved the problem, the girls were happy again and the cutting oil was absolved.

A Deposit Responsibility Problem

Deposits were detected in a machine which utilized both a soluble oil and a grease. Which, if either, was responsible?

As illustrated in Figure 18, the petroleum laboratory fixed responsibility by separately extracting the total fatty acids (TFA) from the deposit, the grease and the soluble oil, and subjecting them to infra-red absorption spectroscopy*. As may be seen from Figure 18, the instrumental traces from the total fatty acids of the deposit and the grease are not only quite similar, but both are quite different from that of the soluble oil, therefore the grease was responsible in some manner for the deposit formation.

* See Pages 1-5, January 1958 issue LUBRICATION.

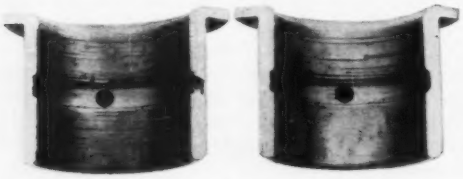

Figure 19 — Worn drive-pinion bushing (sectioned).

An Aircraft Drive Pinion Bushing Problem

An aircraft operator complained of the short serv-

Figure 20 — Bearing surface of drive-pinion bushing.

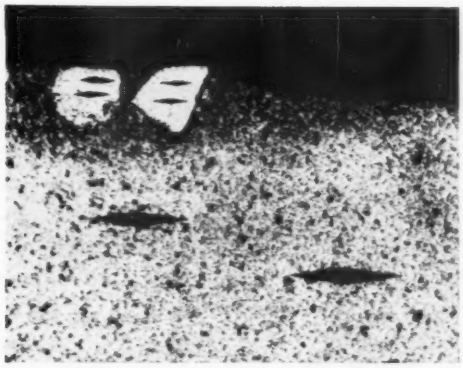

Figure 21 — Photomicrograph of bushing section.

ice life of bronze drive-pinion bushings. Figure 19 illustrates such a bushing which has been cut in two to facilitate examination of its internal bearing surface. The circumferential grooves and specks give ample evidence of bearing damage, but the cause is not obvious. Figure 20, a magnified portion of the bearing surface, indicates that particles of some extraneous material harder than bronze have entered the bearing from the reader's left, ploughed tracks into the bronze and were eventually buried, imbedded or "swallowed up" by the bronze as indicated by the slightly raised "warts" at the right ends of several tracks. Imbedability, the ability to isolate foreign particles and make them less harmful to the journal, is one of the desirable characteristics of a good bearing material.

Figure 21 presents a cross-section of the bearing surface with two partly imbedded foreign particles. The diamond-shaped hardness impressions on these particles and on the bronze not only indicate that the particles are much harder than the bronze but specifically identify them as bits of hardened steel. By painstaking backtracking through the aircraft operator's overhaul procedures, the oil engineers determined that the foreign particles originated as hardened steel "grit" used in a grit blasting operation to clean some steel engine parts. Improved housekeeping by the aircraft operator eliminated his drive-pinion bushing problem.

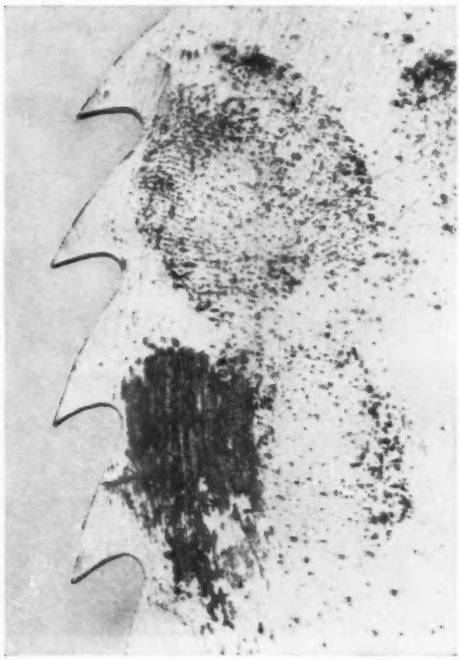

Figure 22 — Rusting of new circular saw blade.

Figure 23 — Corroded tapered roller bearing.

A Rusty Saw Problem

As illustrated in the lower portion of Figure 22, a manufacturer of circular saws began to experience blotchy patches of stain or possibly rust on finished saw blades which destroyed their saleability. Acting upon suspicion and wide experience, the petroleum laboratory exposed the saw blade to further rusting in a special humidity cabinet. By this means the hitherto invisible fingerprints shown in Figure 22 were developed much like the latent image on an exposed photographic film, thereby disclosing their responsibility for the rusting.

This problem was solved by supplying a unique

Figure 24 — X-ray film diffraction equipment.

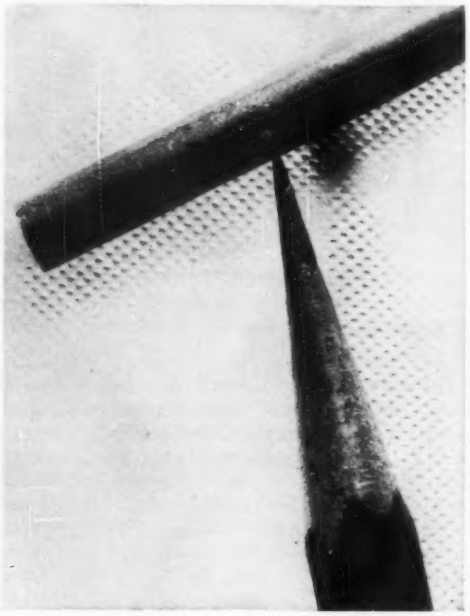

Figure 25 — Perforation in aircraft oil cooler tube.

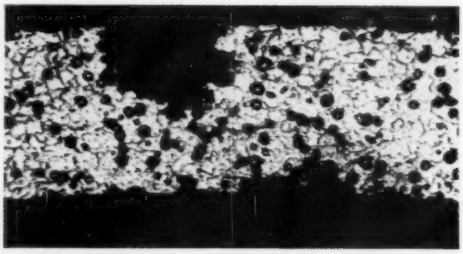

Figure 26 — Photomicrograph of used tube section showing incipient perforation.

rust preventive oil which contained special additives capable of removing and neutralizing the sodium chloride, water, and organic acids that are contained in perspiration and fingerprints. Further protection was afforded by having the workmen wear gloves during manufacture and final packaging.

A Tapered Roller Bearing Problem

A customer submitted the roller bearing portrayed in Figure 23. The original bearing and its lubricant were liberally contaminated with both red and black material. The problem was to determine the nature of the contaminant and its origin.

Using X-ray diffraction equipment illustrated in Figure 24 and described in LUBRICATION for January 1958, the laboratory analyst determined that the contaminant was an iron-oxygen compound and specifically the alpha ferric oxide (Fe_2O_3) which

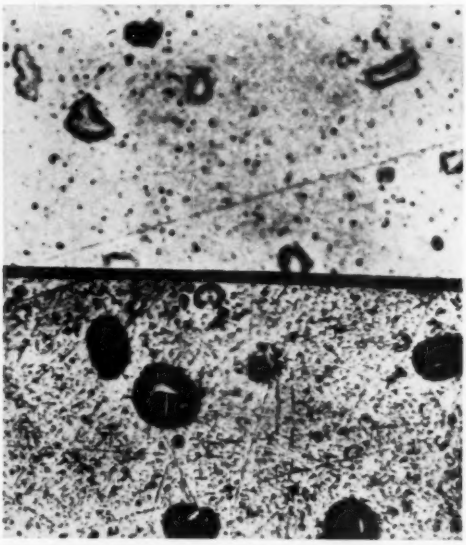

Figure 27 — Photomicrographs of sections from new (upper) and used (lower) oil cooler tubes

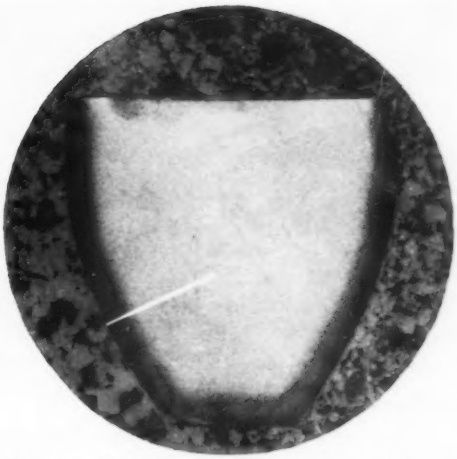

Figure 28 — Photomicrograph of section of spur gear tooth.

is characteristic of fretting corrosion, in turn caused by heavy reversible loading or vibration with little movement. Had ordinary rusting occurred, the contaminant would have been hydrated ferric oxide ($Fe_2O_3 \cdot H_2O$) and the oil engineer would have sought a source of water ingress to the bearing.

An Aircraft Oil Cooler Problem

An airlines operator who was justly proud of his maintenance, suddenly experienced leakage failures in numerous engine oil coolers. These coolers are composed of bundles of many seamless metal tubes, about the diameter and thickness of soda straws, and manufactured from aluminum alloyed with magnesium and silicon. Since the hot engine oil contacted the surface of the tubes, it was an obvious suspect. Figure 25 illustrates the exterior of one of these tubes with the pencil pointing to one of the many tiny holes which gave leakage through the tube wall. Figure 26 presents a highly magnified section of the tube wall, showing two pits in progress of forming a complete perforation together with many black inclusions not immediately explicable.

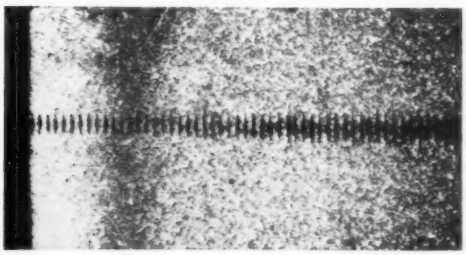

Figure 29 — Hardness measurements near wearing surface of spur gear tooth.

This is an instance where the laboratory was given the extremely difficult task of analyzing a hole: in other words, it was literally expected to work on *nothing*, to find what caused the nothings.

The upper portion of Figure 27, a photomicrograph of a section from a *new* tube, exhibits a series of grey bodies with about the same size, shape, and distribution (though of different color) as those in Figure 25. The laboratory determined that the bodies were magnesium silicide (Mg_2Si). Further investigation developed the most unusual fact that magnesium silicide decomposes when exposed to hot water. To check this possibility, a piece of a new cooling tube was merely boiled in water for a few minutes before obtaining the photomicrograph shown in the lower part of Figure 27. The marked similarity between this latter picture and that of Figure 26 proved that the mysterious *black* "bodies" were actually holes or voids that were left when ordinary hot water had removed the original magnesium silicide bodies.

With this information as a clue, the oil engineer quickly found out that the airline had recently begun to clean out oil cooler tubes with a commercial chlorinated solvent, and realizing that such a solvent might be inimical to engine oil, the airline then

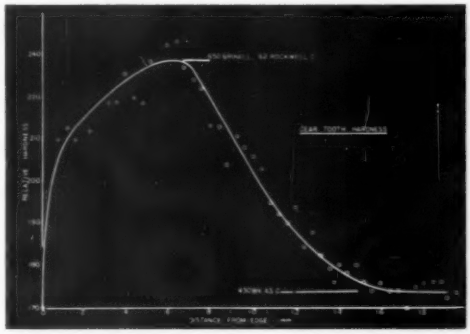

Figure 30 — Variation in gear tooth hardness.

"finish-cleaned" the tubes by blowing steam through them, thus dissolving out the magnesium silicide inclusions and making the holes. This was one of those very rare occasions when meticulous maintenance caused trouble instead of preventing it. Substitution of hot air for steam in the tube cleanup procedure solved the airline's coolant tubing problem.

A Spur Gear Wear Problem

A manufacturer complained of the short useful life afforded by a particular spur gear, the usual inference being that its high wear was caused by an inadequate lubricant. Figure 28 presents a cross-

Figure 31 — Damaged copper-lead bearing half.

section of a representative gear tooth which the laboratory moulded into a mottled bakelite holder, polished to a flat surface and etched to reveal grain structure. For example, the dark band extending inward from the tooth's contact surfaces is a result of the carburizing process used to harden the wearing surfaces. On the basis of this evidence alone, one might presume that the carburization had been quite uniform and that the gear had been adequately hardened. However, unproven presumptions are often incorrect and misleading: by check and recheck a scientific investigator either rejects them or proves that they are reliable substantial facts.

In Figure 28, what superficially appears to be a simple white line is actually composed of more than 50 closely-spaced and diamond-shaped hardness impressions. A closer examination, especially near the contact surface, will reveal indications of the individual diamond impressions. Furthermore, the width of the white line increases as it extends into the interior of the tooth, thereby indicating an apparently normal decrease in hardness.

Figure 29 presents a magnified section of the white line and again to the unaided eye, the lengths of the diamonds seem to increase rather uniformly from the tooth wearing surface at the reader's left. But in Figure 30 which presents a plot of the accurately measured hardnesses, it will be seen that the tooth wearing surface is actually a relatively soft "skin" with greatly reduced wear resistance, and that the desired hardness was buried more than a half-millimeter within the tooth where it was of little use. Further investigation in the manufacturer's plant showed that the atmosphere in his heat-treating furnace was oxidizing and decarburizing the tooth surface: correction to either a neutral or a reducing atmosphere restored the surface hardness of the gears and eliminated the wear problem.

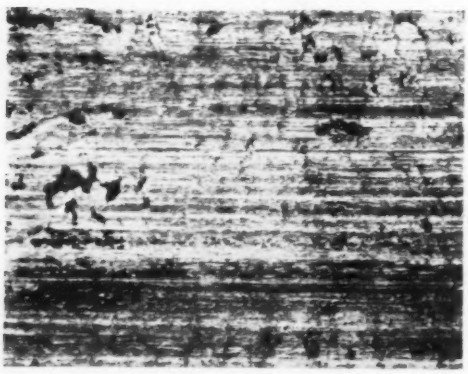

Figure 32 — Surface of another damaged copper lead bearing.

A Copper-Lead Bearing Problem

A copper-lead bearing consists of a layer of a mixture of metallic copper and lead which is metallurgically bonded to a steel back by casting from the molten state or by sintering a powdered compact. It is then formed into a precision bearing like the predecessor unused version of that shown in Figure 31. The copper which gives an unused bearing its readily identified red color is in the form of a matrix or sponge with the interstices filled with metallic lead. Thus the copper which in itself is a poor bearing material is used to furnish strength to the metallic lead, which is an excellent bearing material but with little strength. Because of this mechanical combination of properties, copper-lead bearings give superior performance on crankshafts and connecting rods of heavy duty gasoline and diesel engines.

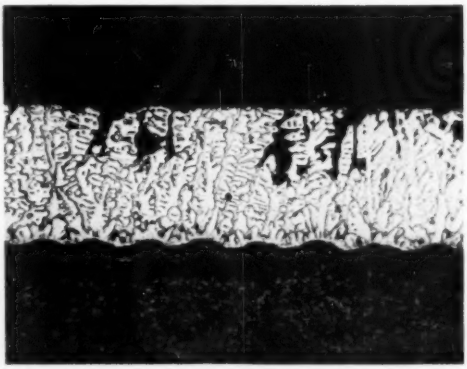

Figure 33 — Photomicrograph showing lead corrosion in copper-lead bearing.

However, like any other bearing material, copper-lead is subject to fatigue, to embedments of foreign materials and to corrosion of either the copper or lead components. The causes and cures for these

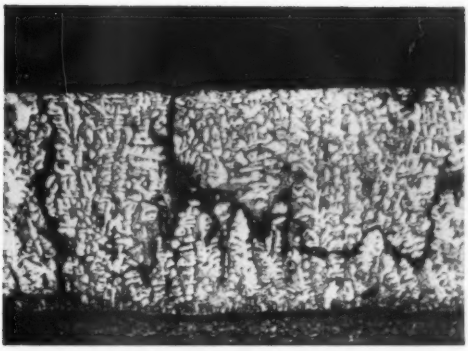

Figure 34 — Photomicrograph showing fatigue in a copper-lead bearing.

various ills are quite different, therefore an accurate diagnosis on a sick copper-lead bearing is always necessary and has previously been quite a problem. For example, and as illustrated in Figure 31, an unaided visual examination of a bearing is of little value and any conclusions based thereon can be very misleading.

Figure 32 presents another example of uncertainty. While the multitude of vertical hairline cracks and the black voids (where the copper-lead material has been removed from the steel backing) both suggest fatigue, was the fatigue preceded and abetted by corrosion? Was the longitudinal grooving caused by solid contaminants in the oil stream or by fragments of the bearing itself? Only a more intensive examination with specialized equipment can accurately answer such questions.

Figure 33 presents a photomicrograph of a cross-section from a damaged copper-lead bearing, with the black bakelite specimen mount at the top, the bearing surface and copper-lead bearing material next below and the steel backing at the bottom. The irregularly shaped white portions are the copper matrix, while its interstices are filled with the grey-colored metallic lead. (Of course, in the color photographs that are advantageously employed in work of this sort, the copper appears in its normal red color while the lead has a white metallic luster.) The wavy boundary between the steel back and the copper lead lining shows the deliberately-coarse turning used by some manufacturers to increase the strength of the bond.

The reader's close attention is now invited to the black voids in the upper portion of the copper lead material, and to the important fact that they are extensions of the grey colored lead component. In other words, something has removed metallic lead to a considerable depth leaving the white copper matrix unchanged. This, then, is an example of lead corrosion. As lead is removed, the copper matrix is left unsupported and easily hammers down to a mass of pure copper fragrants which not only provides a poor bearing, but one with greatly increased running clearance to aggravate fatigue failure even if corrosion is stopped.

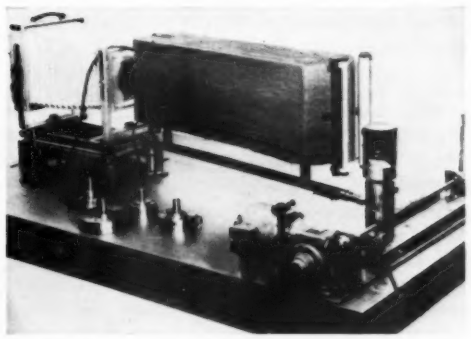

Figure 35 — Special photographic equipment for concave and convex surfaces.

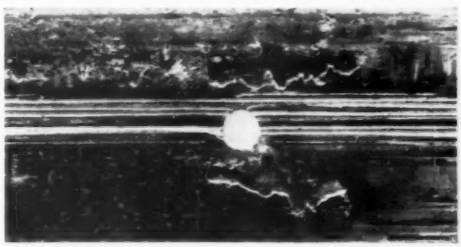

Figure 36 — Planar photograph of concave copper-lead bearing surface.

Though metallic lead is strongly resistant to the action of strong inorganic acids like sulphuric, it is easily dissolved by numerous organic acids like formic (CH_2O_2), acetic ($C_2H_4O_2$), propionic ($C_3H_6O_2$), butyric ($C_4H_8O_2$), and even the "weak" carbonic acid (H_2CO_3) that is formed when rainwater dissolves carbon dioxide from the air. When partly oxidized, organic materials like lubricating oil and some fuels tend to form organic acids, therefore it is probable that the lead attack exhibited in Figure 33 was either *oil* or *fuel* corrosion. Antioxidant additives in lubricating oils, decreased operating temperatures, and controlled drain periods are some of the methods used to prevent this type of corrosion. The bearing surface of some copper-lead bearings has also been coated with a thin layer of indium or a lead-tin alloy, effective corrosion preventives as long as they remain unbroken.

The corrosion of the copper in copper-lead bearings is effectively prevented by modern fuels and

Figure 37 — What happened?

lubricating oils and is therefore so rare that an example can not be presented.

A careful examination of Figure 34 will show that while the multiple black lines are actually cracks through masses of lead, there has been no *removal* of lead. In other words, corrosion has not occurred and the damage is due to the purely mechanical stress type failure called "fatigue".

Two other interesting points are observable in Figure 34. First notice that the lengthy crack on the reader's right is of shape characteristic of fatigue failure since it descends more or less vertically from the surface then spreads laterally to either join another crack or return to the surface. An entire segment of material is thus freed, subjected to hydraulic forces, and eventually ground up into particles small enough to escape through the bearing clearance.

Secondly, the prominent crack on the reader's left has descended vertically to the bond-alloy before branching laterally in both directions. This is an indication that the bond itself is of satisfactory strength, otherwise the vertical crack would have reached the steel backing.

Due to distortions arising from foreshortening of surfaces at oblique angles to the camera axis, cylindrical objects like concave bearings and their convex journals have resisted photography of more than a very limited area. The advantage of an overall picture of such objects with every portion in focus is manifest and is now obtainable with the laboratory-designed-and-built apparatus illustrated in Figure 35. In other words, such a specialized piece of equipment can photographically "unwrap" either a concave or convex surface to produce a flat image. Figure 36 presents such a photograph of a copper-lead bearing that has suffered heavily both from extensive fatigue and considerable grooving by solid contaminants in the oil stream. Notice once more that the edges of the fatigue voids are vertical and that most of the grooving has occurred in line with the central oil-supply hole.

A Complete Failure Problem

A laboratory's successes tend to generate a reputation of complete invincibility. Figure 37 pictures the battered halves of an engine bearing to illustrate that there are definite insurmountable limits to the investigative, imaginative and deductive capacities of the best scientists. Imagine the frustration that is engendered by the receipt of such "evidence" accompanied by the pitifully naive question "What happened?" In a complete failure such as this, the laboratory can be certain only of the obvious – it failed. The resulting ruin is so complete that all evidence that might indicate *how* or *why* it failed has been destroyed. To put it bluntly, in such cases a doctor can do nothing and only the undertaker profits.

SUMMARY

Many modern complex industrial problems can be solved only through the closest possible collaboration between the customer-user and the technical personnel of a major well-equipped petroleum laboratory.

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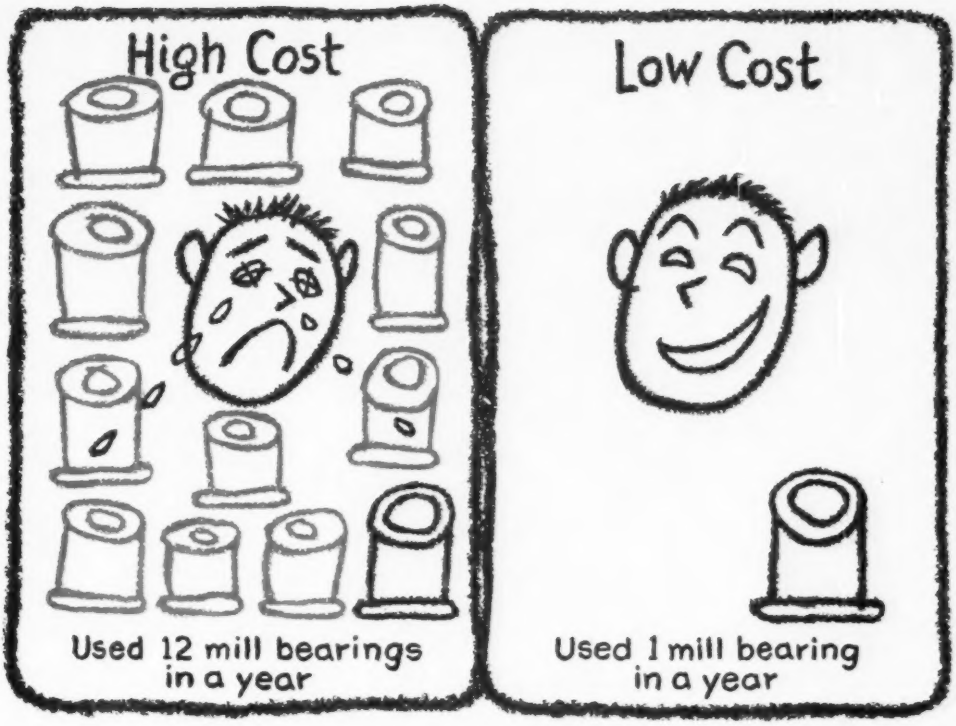

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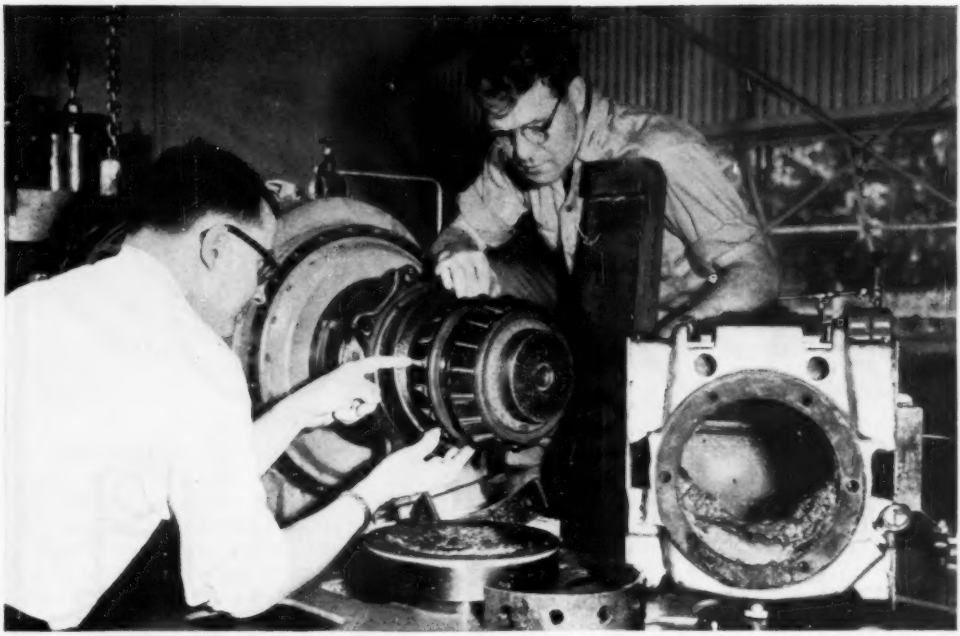

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